

# Kepler Mission Development Challenges and Early Results

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*Abstract*—Kepler is NASA’s first mission capable of detecting Earth-size planets orbiting in the habitable zone of stars other than the Sun. Kepler comprises a space telescope designed to continuously monitor the brightnesses of more than 100,000 target stars, and a ground segment to analyze the measured stellar light curves and detect the signatures of orbiting planets. In order to detect Earth-size planets orbiting Sun-like stars Kepler was designed to provide unprecedented photometric sensitivity and stability. This paper addresses some of the technical challenges encountered during the development of the Kepler mission and the measures taken to overcome them. Early scientific results are summarized.

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## 1. INTRODUCTION

Speculation about habitable worlds orbiting other stars is at least as old as the ancient Greeks. NASA’s Kepler mission will at long last answer the question of how frequently planets of various sizes and orbits are to be found circling stars in our Galaxy, with an emphasis on terrestrial planets orbiting in the habitable zones of stars like our Sun. The habitable zone is that distance from a star where the equilibrium temperature of the planet would permit the existence of liquid water, believed necessary for any form of life we might recognize. Detecting the presence of an Earth-size planet orbiting a Sun-like star is extremely difficult because the planet is so much smaller and less massive than its star, not to mention millions of times less bright. The approach taken by Kepler is to detect the passage of a planet across the disk of its star by measuring the slight drop in brightness caused by the planet blocking some of the star’s light as it passes in front of the star. The passage of a planet across the disk of a star is called a “transit.”

For there to be a transit the geometry must cooperate such that the Earth lies nearly in the planet’s orbital plane.

Assuming that planetary systems are oriented randomly, the likelihood of any planetary orbit being adequately aligned is only about 0.5%, so the vast majority of stars will not exhibit transits. To perform a statistically significant survey, and to have a meaningful null result in the event no transits are detected, the number of stars to be monitored must be quite large. Because it is not known when the transits will occur it is also necessary to monitor the stars simultaneously and continuously. Since transits occur once per orbit, the time interval between transits provides the planet’s orbital period. By measuring the relative drop in the star’s brightness resulting from the transit, and by knowing the star’s size and mass (something astronomers can determine by various techniques) the diameter of the planet and its orbital radius can be determined, and its temperature inferred.

Statistical arguments determine that the survey should include at least 100,000 stars; in fact, Kepler began with more than 150,000 stars, carefully selected to be the most Sun-like. To support continuous monitoring, a single region of the galaxy rich in stars was selected between the constellations Cygnus and Lyra, an area sufficiently out of the ecliptic plane that the Sun does not preclude its being observed year round by a spacecraft. The field of view required to encompass 100,000 stars of suitable type and brightness, even in this star-rich region, is about 100 square degrees, and the plate scale necessary to image and measure individual stars requires a very large focal plane, on the order of 95 megapixels. Because the galaxy is filled with eclipsing binary stars and other phenomena that can mimic planetary transits, false positive detections will be common and methods are needed to identify and reject them. One such method is to measure multiple transits, and assure that the time interval between them is constant to a high degree of precision. Earth orbits the Sun once per year; detecting several transits of an Earth-Sun analog therefore requires a mission life of several years.

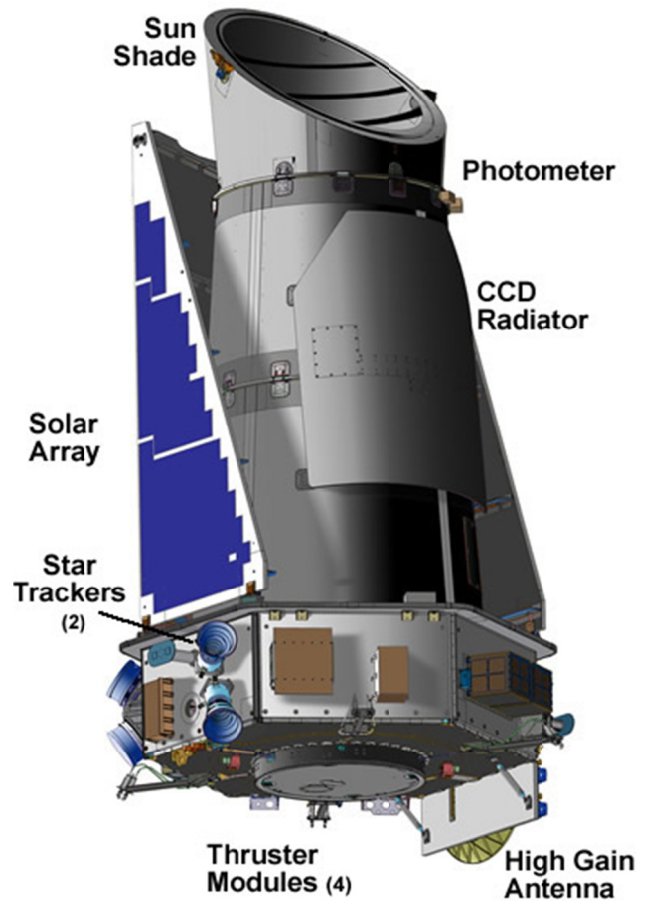
Then there is the question of measurement sensitivity and precision. Given the limiting magnitude of stars in the survey and the number of photons required to achieve an adequate signal to noise ratio, the telescope must be of about 1-meter aperture. If our solar system were observed from another star, the transit of the Earth across the disk of the Sun would result in a drop in brightness of approximately 80 parts per million (ppm) for about 13 hours. To have a secure measurement of transits of this depth and slightly smaller, Kepler’s photometric sensitivity was set at 20 ppm.

Nothing like this level of precision has ever been achieved before. Moreover, stars are known to be variable in brightness, but the only star known to this level of precision during Kepler's formulation phase was the Sun—a single data point! A photometric error budget was developed that assumed stellar variability of 10 ppm (the value for the Sun), leaving 17 ppm for the measurement and ground data processing. This was further subdivided into various contributions from signal shot noise, cosmic rays, read noise and charge transfer efficiency from the focal plane charge coupled devices (CCDs), image smear, pointing jitter, etc.

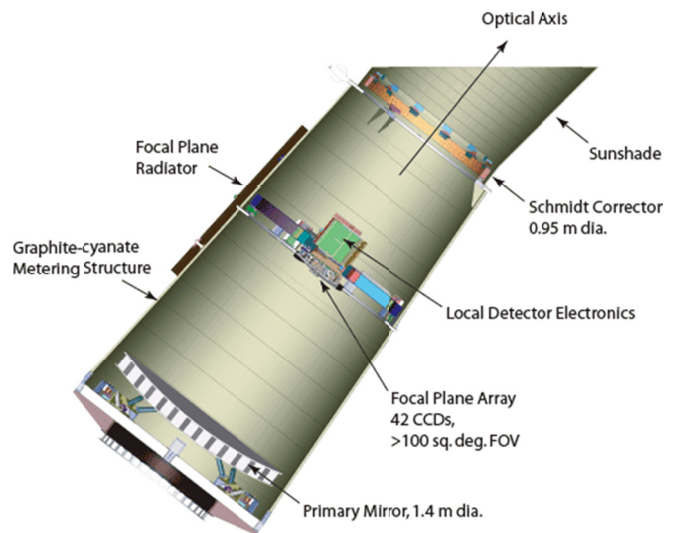
Many technical and programmatic challenges were encountered during the eventful development phase of the Kepler mission. Programmatic challenges are documented elsewhere [1]. Among the more interesting technical challenges were the ability to verify and validate the photometric performance of Kepler prior to launch, the need to make a last minute change to the focal plane drive electronics design due to an electronic part susceptibility to radiation single event effects, and the various systematic noise sources that were discovered during ground testing of the focal plane readout electronics. These challenges and the steps taken to overcome them are detailed in what follows. Finally, some early and spectacular science results from the mission are summarized.

## 2. THE DESIGN OF KEPLER

The Kepler space vehicle consists of a Spacecraft bus and Photometer instrument as shown in Figure 1. The Spacecraft provides electrical power from solar panels, provides command and data handling, communicates with the Earth, controls the pointing of the line of sight of the telescope, and performs various housekeeping functions. The Photometer, shown in Figure 2, consists of a Schmidt telescope having a spherical primary mirror of 1.4 meter diameter; a corrector plate (lens) of 0.95 meter aperture; and a 95 megapixel focal plane detector array assembly (DAA) consisting of 42 science CCDs, 4 fine guidance sensor (FGS) CCDs for pointing control, and the readout electronics packaged on 10 electronics cards. The DAA is located at the prime focus of the telescope, suspended on four spider legs from the telescope housing. The focal plane array is arranged as 25 modules, with the four corner modules allocated to the FGS. Each of the 21 science modules consists of two CCDs. Each of the modules includes a sapphire field flattener lens mounted above the CCDs to correct for field curvature across the module. The fully assembled focal plane array can be seen in Figure 3.



**Figure 1.** The Kepler space vehicle consists of a spacecraft bus and Photometer instrument.



**Figure 2.** The Kepler Photometer (shown in section view) consists of a primary mirror, Schmidt corrector, and 95 megapixel focal plane array assembly.



**Figure 3.** The Kepler Detector Array Assembly (DAA) consists of 42 science CCDs and 4 find guidance CCDs (at the corners), and Local Detector Electronics (LDE), forming a 95 megapixel camera.

Some key performance requirements for the Kepler mission include:

- Measurement of photometric data on at least 100,000 target stars every 30 minutes
- Photometric precision of 20 ppm on a 12<sup>th</sup> magnitude G2V dwarf star (having 10 ppm stellar variability) over a 6.5 hour integration
- Pointing stability of 0.009 arc seconds (3-sigma) per axis over any period of time 15 minutes or longer in duration
- Mission lifetime of at least 3.5 years

In order to meet the extremely high photometric precision requirement it was decided to place Kepler into an Earth-trailing solar orbit rather than into orbit around the Earth. This has the advantage of a stable thermal environment necessary to achieve very stable temperatures. Stable temperatures are key to stable electronics performance, stable optical metrology, and stable pointing stability and repeatability. Since it is necessary to keep the solar array pointed toward the Sun, the Kepler vehicle must be rotated around the telescope line of sight 90 degrees every three months. This changes the portion of the focal plane that each target star falls on, and therefore changes the CCD and readout electronics chain associated with the photometric measurement of any given target star. In constructing the stellar light curves it is therefore necessary to calibrate these and other systematic effects in the data.

#### 4. SINGLE EVENT EFFECT SUSCEPTIBILITY

While the Kepler mission's application of CCD-based, precision differential photometry to detect exo-planets is novel and challenging, for the most part the individual component technologies are mature and didn't represent major risks during development. In general, most of the challenges centered on building the large, complex system, integrating it within cost and schedule constraints, and managing the various noise sources and systematic errors affecting photometric performance. There were, however, some significant component-unique challenges with far reaching implications, one of which we describe here.

Kepler mission requirements for a large FOV (many CCDs), rapid readout rate and low-noise performance, together with tight thermal constraints (imposed by the need to locate the analog-to-digital conversion electronics inside the cold telescope) resulted in a complex, high-density design for the focal plane electronics, called the local detector electronics (LDE). Unique electronic components were selected that could satisfy requirements for high CCD read-out rate (3 mega pixels per second), while preserving well-depth (charge capacity) and offering reasonable linearity without impacting read noise. The LDE parallel and serial clock driver circuitry design employs over 100 hundred Intersil EL7457 quad CMOS drivers. This part had previously been operating successfully in the HiRISE instrument on NASA's Mars Reconnaissance Orbiter. As with all active electronic components intended for use in space, the EL7457 part had been subjected to a radiation effects test program during HiRISE development to assess its sensitivity to Single Event Effects (SEE). SEE represents a family of device responses to the impact of high-energy particles from solar or galactic sources, which can lead to temporary or permanent loss of function. They include temporary Single Event Upset (SEU), temporary and permanent, Single Event Latchup (SEL), permanent Single Event Burnout (SEB), Single Event Gate Rupture (SEGR), and Single Event Transients (SET). Although the EL7457 was operating without incident on HiRISE, the Ball Aerospace Corporation (Ball) radiation effects engineer recognized that the accelerator facility used to test the HiRISE EL7457 component wasn't capable of providing energies sufficient to fully characterize the SEE sensitivity of the device. When the component was retested at the appropriate energy levels, a number of the test parts experienced permanent failure, and at sufficiently high rates to result in an unacceptably high probability of in-flight failure of many Kepler LDE signal chains.

The susceptibility was discovered very late in the development cycle, with flight boards having already been manufactured. A team was organized to investigate how best to mitigate the problem. It was recognized that the HiRISE parts were operated at significantly lower bias voltages (9V) than those on Kepler (13-15V). Subsequent radiation testing confirmed a definite voltage dependence on failure rates, with a sharp demarcation around 12V for all

energy levels. This offered clues on possible failure mechanisms. SEGR and SEB were ruled out based on the strong angle-dependence observed in ion testing. Further testing, followed by photomicroscopy and scanning electronic microscopy inspection of tested parts, indicated the most likely failure mode was Single Event Latchup (SEL).<sup>1</sup> This mechanism was consistent with a strong voltage dependence, which gave confidence in the Kepler project's subsequent decision to reduce the bias voltage of the part.

Adjusting the voltages for the Kepler EL7457's was a delicate undertaking, in particular for those associated with the parallel clock drivers upon which the CCD well-depth is dependent. The three performance impacts of changing the parallel clock-voltage—photometric noise, blooming, and single-pixel saturation for bright stars—had to be balanced in arriving at the design change. In the end, peak differential bias voltage was reduced to 11.75V. This involved changing 200 resistors in the LDE. The change resulted in a significant but acceptable reduction in CCD well depth while reducing the probability of almost certain mission loss (many signal chain failures) to < 0.01%. While critical and necessary for mission success, the EL7457 episode significantly impacted the project schedule. It also affected the LDE signal-chain design with potential consequences on systematic noise sources.

## 5. VERIFYING AND VALIDATING PHOTOMETRIC PRECISION

One of the more challenging aspects of the Kepler mission development was building pre-launch confidence in the Photometer's ability to detect Earth-size transits. While early sub-scale testbed experiments were conducted to demonstrate the basic efficacy of the Kepler approach, running a comprehensive performance test on the assembled flight Photometer was not practical or cost-effective. This challenge—one faced by most large space telescopes—was addressed by devising a layered photometric performance verification and validation (V&V) program for Kepler. This program knitted together a collection of tests, modeling, and analyses into an end-to-end intellectual arc demonstrating confidence in system-level performance.

Originally, the Kepler project had planned an ambitious, nearly end-to-end, performance test on the fully integrated Photometer. This plan called for both a photometric test to verify the 20 ppm differential photometric precision, followed by a 0.01% (~100 ppm) simulated transit test to demonstrate the ability to detect Earth-size transits. The photometric and transit tests called for attaching a complex set of optical test equipment to the top of the Photometer to project a simulated star-field onto one quarter of the aperture, with the ability to simulate transits on selected

“stars”. Both tests would have been conducted at flight temperatures in a large thermal-vacuum chamber over a period of several weeks. The test concept and test equipment design underwent various iterations as the difficulty and cost of such tests became more apparent. At one point the transit test requirement was relaxed by two orders of magnitude to a Jupiter-size transit; but in the end both tests were eliminated due to escalating project cost. A series of trade studies were conducted to assess the relative costs, benefits, and risks of various alternative options, resulting in the selection of the following approach:

The photometric performance verification and validation (V&V) program for Kepler consisted of four primary elements: (1) “camera” cold performance testing, (2) Photometer focus and point spread function (PSF) testing, (3) single-string transit verification testbed (SSTVT) testing, and (4) modeling and analysis to synthesize the results of these tests with missing error sources, such as spacecraft pointing stability. These activities were in turn the culmination of many lower-level tests including the detector electronics, ambient telescope focus and alignment, etc. The concept for synthesizing the results of the four primary V&V activities was based on the photometric precision and SNR error budget for the project, including key error sources such as detector and electronic noise, PSF quality, stray light, pointing stability, and various systematic errors. The above tests and models spanned the range of error sources. The challenge in synthesizing them through analysis included putting them on a common footing despite the different environments in which data were collected.

The Kepler “camera” or DAA consists of the previously described collection of CCDs and LDE. Prior to integration with the Photometer telescope, the DAA was tested as an integrated assembly in a thermal-vacuum chamber. In addition to the usual hot and cold soak and thermal-balance tests, the DAA was subjected to a series of performance tests with the focal plane at its nominal -90 C operating temperature. Performance tests included measurement of read-noise, linearity, cross-talk (electrical and optical), and a simulated optical star-field. Results of these tests provided direct verification of many terms in the photometric precision error budget and also exposed various systematic artifacts (discussed in a following section).

After the DAA was integrated with the telescope to form the Photometer (and subsequently aligned via ambient testing), the entire Photometer underwent end-to-end Cold Focus and PSF testing in a large thermal-vacuum chamber. This test and the facility in which it was conducted were unique. The test was implemented in the Brutus thermal-vacuum chamber at Ball supported by a new piece of test equipment, the Vertical Collimator Assembly (VCA). The VCA can project a large (>1 meter diameter) collimated, white-light optical beam into the aperture of instruments or telescopes (Figure 4). The entire VCA structure is kinematic and athermalized, and the optical alignment of the system is actively maintained during testing using continuous,

<sup>1</sup> Single Event Transient (SET) followed by a destructive cascade effect in the device was not fully ruled out given the complexity involved in modeling the device.

independent metrology. Periodic calibration during the test involved translating the test article out of the beam to allow auto-collimation via a large reference flat mirror. Kepler was the first space telescope system to undergo testing in this facility. For the Kepler Cold Focus and PSF test, both the integrated flight Photometer, and the Spacecraft flight computer and Photometer power supply, were placed in the Brutus chamber.<sup>2</sup> The VCA provided full-aperture illumination of the photometer with a single point source. The VCA's adjustable base was used to tip and rotate the photometer to assess various field-points across the Kepler FOV. The test, conducted over several weeks, included running through-focus tests, PSF characterization, and ghosting (internal stray light) evaluation at different field points. It also provided some assessment of the FGS CCDs, including phasing. It was this test environment, operating across various temperature regimes, which offered an end-to-end assessment of the photometer photometric noise for a single star, albeit without flight-like pointing jitter/drift.

With the elimination of the multi-star photometric test, the Kepler V&V program needed to “boot-strap” the single-star noise performance demonstrated in the Photometer Cold Focus/PSF Test to a flight-like multi-star environment, preferably one including simulated pointing jitter/drift. This was accomplished through the use of the SSTVT. The SSTVT was based on the original Kepler Technology Demonstration Testbed at NASA's Ames Research Center [2]. The original testbed included a sub-scale mockup of the Kepler photometer (wide-field optics and non-flight detector and electronics) along with a unique set of optical test equipment, including a star plate with dozens of simulated stars of various magnitudes (driven by a white-light source and integrating sphere). Earth-size transits could be simulated on a subset of the stars by passing small currents through tungsten wires strung across some of the holes in the star-plate, changing the wire's thickness slightly. For the SSTVT, the testbed was augmented with a single flight-like CCD module and an engineering model board-pair for the LDE (the latter essentially representing a “slice” of the flight DAA). A series of tests were conducted in the SSTVT in parallel with the aforementioned flight system tests. The SSTVT tests, while impacted by non-flight-like mechanical instability and other systematic errors, offered direct evidence that the photometric precision and transit detection signal-to-noise-ratio (SNR) requirements could be met. This “top-down” verification approach was compared with a “bottom-up” estimate of precision and SNR derived from model projections and the noise measurements from the flight-like DAA and PSF tests.

By conducting the independent tests in different environments and comparing results with the help of models, the V&V program demonstrated confidence in the Kepler photometer and associated data processing algorithms. This confidence would prove pivotal in the

final months before launch in assessing system robustness in the face of the various systematic noise sources uncovered by the test program.

## 5. SYSTEMATIC NOISE SOURCES

The most challenging aspect of achieving ppm-level photometric performance is the control and calibration of systematic noise sources. The Kepler mission is designed to detect the 80 ppm signal from Earth-Sun equivalent transits. This precision requires strict instrument stability on time scales in excess of days and noise levels, including systematic errors, of about 20 ppm. Several instrument-induced variations in the CCD readout bias pattern, some of which are time varying, limit ultimate precision in portions of the Kepler field of view. Two principle sources of noise include 1) crosstalk between the 42 science CCDs and the four FGS CCDs, and 2) a high-frequency low-level oscillation on 33 of the 84 readout electronics channels. Crosstalk produces a slow time-varying synchronous pattern in the CCD black image. The oscillations result in a time varying Moiré pattern and rolling “bar” in the affected channels (see Figure 5). When the frequency of oscillation changes, the “bars” move in the affected readout frames, and the interference fringes of the Moiré pattern shift spatially. Both of these effects are highly temperature dependent. By ordinary standards Kepler vehicle temperatures are extremely stable, varying by only a few degrees C over three months. However, even small temperature variations can result in noise that mimics Earth-sized transit signatures.

The systematic noise sources arise from subtle design aspects associated with board layout, robustness against part-to-part variation, and thermal management. Several factors contributed to this. As mentioned previously the requirement for compactness of the DAA, located at the telescope prime focus, resulted in very tight packaging of the electronics boards, which comprise over 20,000 individual parts. The 10 boards are arranged in five pairs, each pair serving 10 CCDs. Each CCD has two readout channels for a total of 20 readout channels per board pair. The same readout circuit design is replicated 20 times using slightly different board layouts. Nine of the twenty layouts resulted in unstable pre-amplifier circuits, due in part to low stability margins, and in part to susceptibility to high frequency parasitics and part-to-part impedance variations. The circuits which oscillate do so at very low amplitude, and only over a limited temperature range of a few degrees C. They do not all oscillate at the same temperature. The four FGS CCD readout electronics are packaged on the two outer board pairs, in addition to the science CCD readouts; hence they share power and ground lines. This, together with the fact that the FGS CCDs are read out at a different interval than the science CCDs, results in complex crosstalk.

The DAA thermal design was challenging. The CCDs are cooled to -90 C by heat pipes extending along the legs of the spider supporting the DAA, whereas the readout electronics,

<sup>2</sup> The project team considered running this test on the fully integrated spacecraft but stack height limitations in the VCA precluded this.

located only a few cm away, operate at about +30 C. Great effort was made to minimize power dissipation in the readout electronics, including power cycling the preamplifiers for each readout cycle. This resulted in the amplifiers never achieving thermal equilibrium. Transient temperature change during the read cycle causes the frequency of the oscillation to “chirp,” contributing again to a complex noise signature. In retrospect, such severe power minimization measures were unnecessary; heat rejection from the LDE was more efficient than originally thought. By the time this was realized, however, it was too late to alter the electronics design. This appears to be an example of conservatism in one area (thermal design) forcing troublesome compromises in another (electronics design). It might have been better to scrub out the conservatism early on to prevent unnecessary complexity downstream.

An excellent test program to characterize performance was planned and executed. It was progressively more flight-like with respect to configuration, integration time, thermal stability, and data analysis. As can be seen in Table 1, both the crosstalk and evidence of the preamplifier oscillation were observed early on in the board-level testing. Initial assessment of the crosstalk, however, suggested no significant temporal variation, and it was thought that simple subtraction during calibration would be adequate. It was not until the flight system thermal vacuum test (which occurred over a nine day duration with much more stable temperatures) that slow noise variations were seen that might be confused with Earth-sized transit signatures. The preamplifier oscillation was more difficult to discern. The first evidence was seen in board-level testing, where the noise in a few channels changed from test to test. In one test noise would behave as predicted by models, in the next it would be higher. At the time this was thought to be an artifact of the test set up. In retrospect it was due to the temperature dependence of the oscillation. The next clue occurred during the focal plane thermal vacuum test. Here the noise in certain channels decreased with temperature, whereas typical noise sources should increase with temperature. In addition, Moiré patterns were observed in the CCD black images. It was at this time that a root cause for the low-level oscillation was first postulated. The noise,

when averaged over an integration period, at first looked Gaussian and appeared to meet requirements, so the decision was taken to proceed as is. In retrospect, the noise appeared “white” because the fluctuation in readout electronics temperature was sufficient to cause the frequency of oscillation to shift rapidly, moving the Moiré patterns across the pixels on time scales small compared to the integration time. It wasn’t until Photometer-level thermal vacuum testing, where temperature stability was much higher, that the frequency change over an integration was small enough that photometric variations which could be mistaken for planetary transits were present.

Both these systematic noise sources could have been significantly reduced by design changes. However, by the time they were sufficiently understood, fixing them in hardware would have been very expensive and would have postponed the launch by many months. It was decided in the end to proceed to launch on the basis that the systematic noise effects covered a sufficiently small portion of the focal plane area, and that ground data processing techniques could sufficiently mitigate them. Software calibration techniques have been developed and continue to be refined by the science data analysis team, with excellent results thus far.

## 5. EARLY MISSION SCIENCE RESULTS

Kepler was successfully launched into an Earth-trailing solar orbit on March 6, 2009. Following on-orbit checkout initial observations were made of stars in the Kepler field of view, including three stars known from ground observations to exhibit transits from large orbiting planets. These were immediately detected by Kepler with such high precision that the secondary transit of one planet passing *behind* its star was detected. This was significant because the secondary transit depth was similar to the transit signature of an Earth-size planet transiting in front of a sun-like star, confirming the ultimate sensitivity of Kepler. At the time of this writing Kepler has identified hundreds of candidate exo-planets awaiting confirmation, and has announced discoveries of nine new planets orbiting seven stars in the target field, including the first secure detection of a rocky planet (Kepler 10b), the smallest planet thus far discovered outside the solar system [3].

**Table 1:** Kepler test program identified clues to systematic noise

		Ambient Engineering single board pair	Ambient Flight single board pair	Focal Plane Thermal Vacuum Test	Photometer Thermal Vacuum Test	Flight System Thermal Vacuum
Date		Jun-06	Apr-07	Sep-07	Mar-08	Sep-08
Integration time		6 sec	6 sec	30 min	3.5 days	9 days
Electronics Temperatures		about 50C	about 50C	-40C to 65C	65C, 30C	30C
Electronics Temp Stability		>5C swing	>5C swing	>1C swing	0.001C	0.001C
Crosstalk		X	X	X	X	X
Crosstalk variation						X
Oscillation	Unstable noise	X	X	X	X	X
	Neg. temp dependence			X	X	
	Varying Moire patterns			X	X	X
	Rolling Band				X	X

## 6. ACKNOWLEDGEMENTS

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## BIOGRAPHY



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**Figure 4.** Kepler inside the Brutus thermal vacuum chamber at Ball, integrated with the Vertical Collimator Assembly (VCA), enabling end-to-end optical testing.

Photo of Frerking:



Photo of Fanson:

